Electric Machines Roadmap 2020

Narrative Report

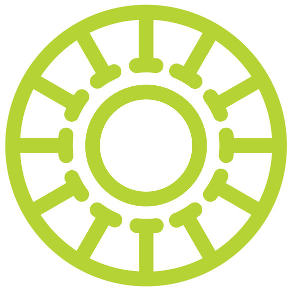
February 2021 | Version 1.0

automotive council UK
ADVANCED PROPULSION CENTRE UK

Overview: Electric Machines

The demand for e-motors is increasing significantly, with over 500 automotive EV models expected globally by 2022* and sales reaching 8.5 million globally by 2025. In the EU, sales of electric cars already match those of diesels.

- Challenges in the development of electric machines include; improving the performance (particularly power per unit volume), lowering cost for mass-market adoption, reducing the dependence on materials whose long-term supply is not assured and minimising the environmental impact of manufacturing and end-of-life recycling.
- Better system performance can be realised through novel architectures and tighter integration of multiple functions within a drive unit.
- As designs become more compact, new materials and thermal management strategies will be needed to meet the demanding requirements for electrical and thermal insulation in such a small space.
- Materials are being developed across many fronts. New form factors and alloying can improve the performance of copper windings, while in the long term, advanced nanomaterials could offer a step change in performance. The dependence on heavy rare earth materials for permanent magnets needs to be reduced. Increasing recycled content, greater use of secondary rare earth materials and alternative manufacturing methods such as polymer bonding offer opportunities. There is scope for further enhancement of electrical steels, with developments such as tailored amorphous metals in the long term. Soft magnetic composites could become more widespread in automotive applications, provided materials can be optimised and manufacturing costs reduced significantly.
- The windings are critical to reducing machine losses. Alternative winding strategies and pre-formed or 3D windings could deliver improved performance. For rotors and stators, new production methods are needed to improve material yields.
- Turning to the environmental impact, recycling electric machines economically with minimal environmental impact is challenging. Reducing the reliance on wet processes, for example, in motor assembly could increase the efficiency of production and make disassembly and recycling easier. Design for disassembly and recycling will be ever more important in the short term, although it is challenging given the increasing integration and compactness of designs. Over the long term, it will be important to address the energy intensity of many of the manufacturing processes. Life-cycle analysis across the entire value chain will become vital.



*Bloomberg BNEF, Electric Vehicle Outlook 2020

A full glossary is provided at the end of this report

Foreword and Acknowledgements

The APC would like to acknowledge the extensive support provided by industry and academia in development and publishing this roadmap.

We are grateful to the Automotive Council for entrusting us with the product and technology roadmaps refresh and their continued support.

This work has received significant support from BEIS (Department for Business, Energy and Industrial Strategy).

Neville Jackson
On behalf of the
UK Automotive Council

I am delighted to share the 2020 automotive propulsion technology roadmaps developed closely in collaboration with industry by the Advanced Propulsion Centre. These roadmaps define critical future targets and the most promising pathways to achieve a decarbonised and more sustainable future vehicle parc. They are an essential tool in developing a focused R&D agenda, particularly relevant for collaborative innovation.

The roadmaps build on the foundations of original UK Automotive Council roadmaps and developed further by the APC in 2017. These have been refreshed to reflect the urgency in transitioning to the UK target of net-zero emissions by 2050. The rate of change in propulsion technologies has accelerated rapidly in recent years; electrified vehicle adoption is on the rise, battery prices have come down faster than previously forecast, alternative zero-emission technologies like fuel cells are maturing at significant pace and clean fuels for combustion, including hydrogen, are emerging to replace existing fossil fuels.

However, there are significant challenges to overcome as the rate of change must increase further, requiring more intensive R&D and commercialisation that will deliver affordable products to market that are even more attractive for consumers. The 2020 technology roadmaps have been developed by industry expert surveys and panels, delivering a consensed view of future automotive propulsion targets, technologies and timescales.

Our aim with this report is to support the automotive sector with insights and a common technology focus to accelerate and deliver world-class solutions. The roadmaps are an important source of information in building collaborative R&D opportunities to address future mobility challenges, goods transport and off-highway vehicle research and development.

Prof Barrie Mecrow
Newcastle University,
APC Spoke for Electric Machines

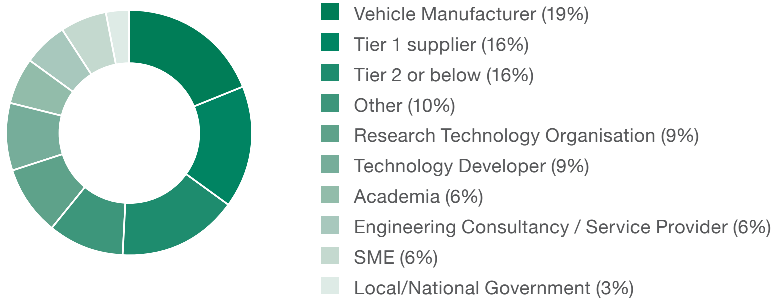
We are at a time of enormous and very rapid change in the automotive industry as vehicles transition to electric propulsion. Our aim is to keep the UK at the forefront of the electric revolution by setting out an ambitious, but realistic journey and goals for electric traction motors. The UK Automotive Council roadmap, supported by the E-Machines Spoke, has received input from many key players in industry and academia which will help guide us to meet the 2030 government targets for all electric propulsion.

To gain international leadership, the UK must develop electric machine innovations and manufacturing technologies in tandem, whilst harnessing the broadest range of skills possible.

Insights from the 2020 Industry Experts Online Survey

Key challenges for the industry include the high dependency on magnet supply from China, increasing demand for driveline component integration and environmental considerations for LCA.

A range of industry specialists responded to the online technology survey carried out in September 2020:



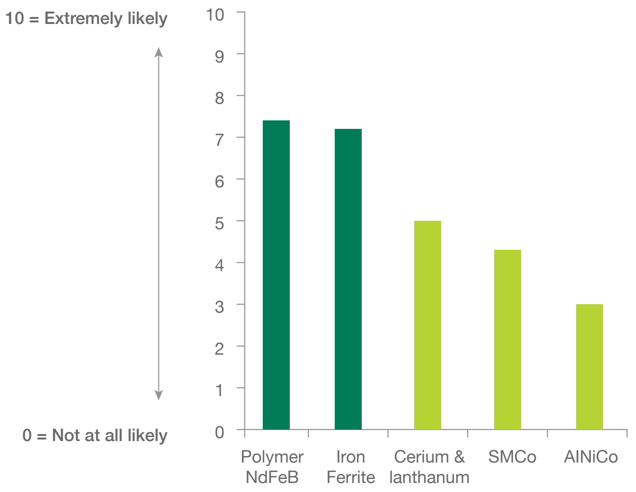
Top three hot topics from the experts

1 The dependency of magnet supply from China exposes the market to price fluctuation and security of supply issues.

2 Compact, low-cost designs are driving greater integration of e-machines into driveline components together with power electronics. These present challenges for serviceability, disassembly and energy-efficient end-of-life recycling.

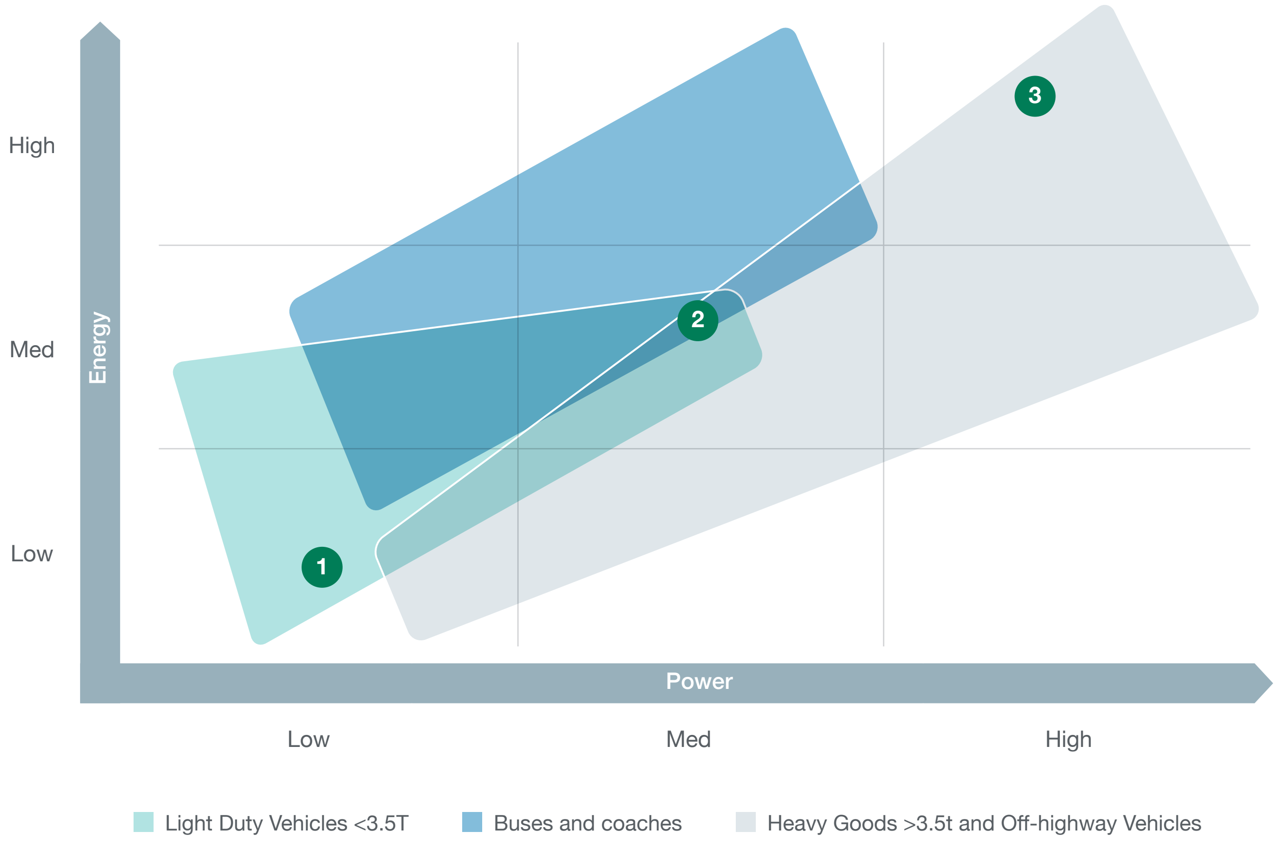
3 Environmental considerations for raw material extraction and refinement, energy-efficient manufacturing and end-of-life LCA need more attention.

Survey result: Magnetic materials most likely to be adopted in EVs alongside sintered NdFeB



Energy-power spectrum across applications

Propulsion systems are tailored to specific power and energy demands, based on their use case and duty cycle. The graph below presents an outline of principle mass-market products.



The 2020 roadmap provides values for (1) Cost effective, high volume indicators.

Values for (2) Power dense, high performance and (3) High power, ultra-high efficiency applications will be developed with industry in due course.

1 Cost effective, high volume orientated:
Achieving economies of scale at a low cost is paramount for these products. Applications include high volume passenger car and delivery vans (majority 400V).

2 Power dense, high performance orientated
High power densities are required with cost a less decisive factor. Applications include performance passenger cars, buses and some medium duty vehicles (800V prevalent).

3 High power, ultra high efficiency orientated
High power densities and reliability are needed for these applications but efficiency is key to maximise energy use. Applications include 44 tonne trucks and large, off-highway vehicles (700-1,200V).

Technology indicators for cost effective, high volume applications

Technology indicators that industry is likely to achieve in a mass-market competitive environment. All the cost and performance metrics are ambitious, but relate to the same technology.

		2020	2025	2035
Electric Machine Indicators	Cost ($/kW)	6	4.8	3.3
	Volumetric Power Density (kW/l)	8	25	30
	Gravimetric Power Density (kW/kg)	4	8	10
	WLTP Average Efficiency	93%	95%	97%

The below table represents the indicator specifications used for the roadmap. These are for reference only, and do not reflect a target spec.

Electric Machine Indicators Spec	2020	2025	2035
Peak Power	100kW	100kW	100kW
Continuous Power	50kW	50kW	70kW
Input voltage (nominal)	400V	400V	800V
Output current (max)	450A rms	450A rms	225A rms
Coolant inlet temperature	65ºC	65ºC	65ºC
Production volume	>100k	>100k	>200k

Notes:

- The electric machine indicators above refer to 1 **Cost effective, high volume** applications. See page 1 for other indicators which present other product applications.
- The cost indicator represents the price an OEM would be expected to pay for a cost effective, high volume electric machine.
- All masses and volumes include the active electromagnetic components of the motor, the shaft, casing and any heatsinks. They should not include the mass of any cooling fluid, external radiator or fluid pump. Electrical filters and power electronic components should not be included.
- Continuous power and torque should be sustainable for at least 15 minutes.
- Power is Net Power, as defined in ECE R85.
- WLTP Average efficiency refers to powertrain efficiency. This should be read as the motor, inverter and the transmission achieve the indicated efficiency value for 2025 and 2035.

Technology indicators
In 2020, these replace targets in the roadmaps, providing a direction of travel and an approach to measuring best-in-class performance for this technology.

Technology indicators for cost effective, high volume applications

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2020 indicators reflect evidence from industry on the best-in-class numbers for cost-effective, high-volume applications.

Cost: Significant cost reductions are achievable through economies of scale. For the targets listed here, reducing cost is paramount to support the uptake of electric vehicles.

Power density is important to minimise weight and free up packaging space.

Efficiency: The WLTP test procedure offers a standard and consistent way of evaluating efficiency improvements for e-motors within vehicles. Although electric machine efficiencies are high, there is room for further advances and loss reductions.

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Roadmap 2020

Electric Machines

Technology Roadmap

Technology indicators for 2020-2035 can be seen on page 2

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This roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass market adoption. Specific application-tailored technologies will vary from region to region.

Dark bar: *Technology is in a mass market application. Significant innovation is expected in this time frame*

Transition: *Transitions do not mean a phase out from market but a change of R&D emphasis*

Dotted line bar: *Market Mature – technology has reached maturity. Likely to remain in mass market until it fades out where it's superseded*

Machine Architectures and Integration

- Advanced architectures (e.g. PM free, axial flux, transverse, flux, new rotor designs, high speed motors) → Radical architectures (e.g. HTS, coreless rotors)
- 1st gen integrated drives (packaged closely) → Functionally integrated drives (i.e. housing, embedded electronics, high speed gearbox)
- New machine designs via enhanced simulation techniques → ALM-enabled new machine designs with adaptive / flexible features

Thermal Management

- Isolation materials for electrical strength and thermal conductivity (e.g. film insulations) → Advanced electrically insulating, thermally conductive materials
- Direct liquid cooling (i.e. windings termination, laminations) → Advanced cooling concepts (i.e. phase change cooling)
- Integrated thermal management (e.g. converge inverter and motor cooling)

Material Developments

Windings

- Enhanced copper windings (e.g. alloys, litz wire, laminated, enhanced coatings) → High performance windings (e.g. graphene, HTS)
- Alternative low-cost windings (e.g. aluminium, aluclad) → Cost-competitive ALM windings with alternative materials

Hard Magnetics

- Reduced heavy rare earths content → Blends of primary and secondary rare earth magnets → 100% recycled rare earth magnets
- Alternatives to sintered NdFeB for mass market applications (e.g. iron ferrite, SmCo, bonded NdFeB)

Soft Magnetics

- Enhanced e-steels (i.e. higher Si content, thinner laminations) → Cost competitive next gen. e-steels (e.g. CoFe alloys, localised properties)
- SMCs tailored for high volume automotive (i.e. smaller grain sizes, reduced saturation)

Manufacturing Innovations

- High volume winding techniques with high fill factor (e.g. cont. hairpin) → New winding processes for high performance (e.g. casted windings, ALM)
- Reduced wastage of stator / rotor stacking (e.g. slinky stators) → Net shape, zero waste integrated magnetics
- Enhanced magnet manufacturing processes (e.g. laminations)
- Reduced wet manufacturing processes in machine assembly → Eliminate wet processes

Life Cycle

- Pilot recycling plants → Mass market e-machine recycling → Closed loop value chain for e-machines
- Design for LCA and disassembly → Highly decarbonised manufacturing and recycling → LCA focussed value chains

2020 | 2025 | 2030 | 2035 | 2040 | ...

Primary Technology Themes

Machine Architectures and Integration	**Machine architectures and integration** show innovations in the magnetic and mechanical design of electric machines and how they are integrated into the wider powertrain system. Advanced concepts through enhanced design, simulation tools and manufacturing methods are highlighted here.
Thermal Management	**Thermal management** techniques are vital for enabling high-speed, power-dense machines. Advanced thermal management materials, such as insulation and impregnation resins, are detailed here, as well as active cooling strategies, such as liquid and air cooling.
Material Developments: Windings; Hard Magnetics; Soft Magnetics	**Materials Developments:** **Winding materials** articulates two development routes: cost effective winding materials such as aluminium and high performance winding materials that improve upon the performance of copper. **Hard magnetics** represent the largest cost in most EV traction motors, so reducing the cost through material, supply-chain and manufacturing innovations is essential. Reducing the automotive industry's reliance on primary rare earth materials and moving away from sintered NdFeB magnets are potential innovation areas. **Soft magnetics** show the parallel material innovations for both electrical steels and soft magnetic composites. Electrical steels will become increasingly thinner, with more silicon added in for conductivity, whereas SMCs require innovations to make them suitable for the automotive mass market.
Manufacturing Innovations	**Manufacturing innovations** are crucial and must go together with improved materials if solutions are to be scaled up for automotive applications. High-volume winding techniques, advanced magnetic manufacturing methods and reducing wet processes in machine assembly are explained in this section.
Life Cycle	**Life cycle** includes the carbon intensity, environmental impact, resource consumption and recyclability of electric machines and their supply chains. Only by improving all these elements can electric vehicles be a truly sustainable solution.

Machine architectures and integration

Novel architectures and greater functional integration can deliver more compact design with better performance, as well as providing opportunities for radical new materials, design methods and manufacturing approaches.

Machine Architectures and Integration

1 Advanced architectures (e.g. PM free, axial flux, transverse, flux, new rotor designs, high speed motors) → Radical architectures (e.g. HTS, coreless rotors)

2 1st gen integrated drives (packaged closely) → Functionally integrated drives (i.e. housing, embedded electronics, high speed gearbox)

3 New machine designs via enhanced simulation techniques → ALM-enabled new machine designs with adaptive / flexible features

Thermal Management

Material Developments: Windings, Hard Magnetics, Soft Magnetics

Manufacturing Innovations

Life Cycle

1

Advanced architectures

Key considerations when designing electric machines are stator and rotor geometries, the size of air gap, winding strategies (concentrated versus distributed), flux paths and the location and shape of permanent magnets.

Radial flux machines have been common in high-volume, cost-effective EV applications. For power-dense applications, axial flux machines are also being commercialised. For these architectures, the coils are placed axially round the stator and the rotor is turned through 90°. This creates a compact motor and reduces the need for electrical steel for the back iron. Given the straight flux paths, grain-orientated steels can be used instead to improve efficiency further.

There are opportunities for radical changes in stator and rotor architectures in the future. Examples include motors that use high-temperature superconductors, coreless rotors or superconducting magnets.

2

Integrated drives

To minimise packaging space and reduce weight, integrated drives are becoming increasingly common. Varying levels of sophistication exist, with the first iteration being the inverter, motor and transmission packaged closely together and optimised to operate efficiently as a system.

To achieve higher power densities and better system efficiencies, functionally integrated drives are being explored. These systems will remove high-voltage cabling, possess a single thermal-management system and share a housing. In the longer term, more high-performance and niche applications could opt for 3D printed drives, where power electronics are embedded on the stator or rotors.

Challenges with integrated drives include their manufacturability; effective cooling systems; graceful failsafe mechanisms; and achieving higher switching frequencies to support smaller electrical machines.

3

Enhanced designs via simulation

Increasingly sophisticated multi-physics design tools will enable greater freedoms when creating new electric machine topologies. Thermal, magnetic, electrical and mechanical elements can be combined to arrive at the optimal electric machine design.

As additive layer manufacturing becomes cost effective and more common, it will enable radical new designs to be manufactured. This could include the 3D printing of intricate magnetics or windings to support high-performance electrical machines. For certain applications, 3D printing of entire motors could be possible. This would allow integrated hard and soft magnetics and embedded power electronics.

2020 2025 2030 2035 2040 ...

Thermal management

New materials and more targeted cooling methods will be needed to meet the demanding requirements for electrical and thermal insulation in a small space.

Roadmap 2020
Electric Machines | Technology Roadmap

Machine Architectures and Integration

Thermal Management

1. Isolation materials for electrical strength and thermal conductivity (e.g. film insulations) → Advanced electrically insulating, thermally conductive materials
2. Direct liquid cooling (i.e. windings termination, laminations) → Advanced cooling concepts (i.e. phase change cooling)
3. Integrated thermal management (e.g. converge inverter and motor cooling)

Material Developments: Windings; Hard Magnetics; Soft Magnetics

Manufacturing Innovations

Life Cycle

2020 | 2025 | 2030 | 2035 | 2040 | ...

1 Insulation materials

Electrical insulation materials also act as thermal insulators and hence provide a barrier to the removal of heat, so considerable efforts have been directed at making them thinner. However, the fast switching of voltage by the inverter requires advanced insulating materials to counteract the high dV/dt levels. The two key criteria for evaluating whether a new insulation material is better are: its voltage per unit thickness the insulation can withstand (dielectric strength); and how much heat is generated by the flow of AC across it (dielectric loss coefficient). Improvements in these elements must not compromise the insulation's operating temperature or the flexibility of the coating. Materials such as PVDF (polyvinylidene fluoride) and FEP (fluorinated ethylene-propylene co-polymer) are likely to be adopted as higher voltage powertrains become more common.

2 Active cooling

A range of different cooling options exist for EV electric machines. These range from cost-effective methods such as forced air cooling and passive cooling, to more complex methods such as hollow shaft rotor cooling, outer jacket liquid cooling and oil spraying. For very high-performance applications, immersion cooling in dielectric oils for hot spots such as winding terminations is another option. Oils and glycols for EV thermal management differ from traditional ICE formulations and need to consider anti-wear performance, friction reduction, efficiency, electrical compatibility and insulation.

In the long term, there is the opportunity for more advanced thermal management strategies such as employing phase-change materials to store useful heat energy or convert it to electrical energy.

3 Converging cooling systems

The move towards integrated drives makes converging thermal management a cost-effective and practical innovation step. The separate cooling loops for inverters and motors add complexity and cost. However, merging cooling systems presents unique challenges. Motors and power electronics often operate at different temperatures, therefore designing cooling systems that can manage the thermal disparity between both technologies presents significant system engineering challenges.

Material developments

New form factors and alloying can improve the performance of copper windings, while in the long term advanced nanomaterials could offer a step change in performance.

Machine Architectures and Integration

Thermal Management

Material Developments
- Windings
- Hard Magnetics
- Soft Magnetics

Manufacturing Innovations

Life Cycle

1

Winding materials that improve performance

Alternative higher-performance windings can be achieved through better materials and better winding design. To improve fill factors, square wires which can fill the slot area more effectively than round wires are commonly adopted. However, square wires are much more difficult to work with, because if they twist during the winding process, they can counter-productively reduce the fill factor. Other design improvements include using thin multi-stranded wires (e.g. litz wire) or laminated windings to reduce the AC winding loss.

In the long term, it is possible that advanced materials such as carbon nanotubes embedded in copper or on the surface, graphene, nanomaterials or high-temperature superconductors could be commercialised in specialist high-power and performance applications. These would offer a step change in conductivity, thermal performance and lower losses, but come at a price premium.

1. Enhanced copper windings (e.g. alloys, litz wire, laminated, enhanced coatings) → High performance windings (e.g. graphene, HTS)
2. Alternative low-cost windings (e.g. aluminium, aluclad) → Cost-competitive ALM windings with alternative materials

2

Cost-effective winding material

Winding materials offer the potential to dramatically lower costs. Aluminium windings are cheaper, lighter and more readily recyclable with steel compared to copper, thus making them an attractive replacement. However, with lower conductivity the challenge is to design an electric machine with aluminium windings that maintains the weight, size and power density of copper-wound machines, while overcoming the termination challenges. Using aluclad windings, an alloy of copper and aluminium, could be a hybrid solution that reduces costs but maintains some of the performance characteristics of copper.

In future, advanced additive-layer manufacturing has the potential to replace complex winding processes and provide new configurations. However, additive-layer manufacturing methods will need to become more commonplace and cost competitive to be used in mass-manufacturing.

2020 | 2025 | 2030 | 2035 | 2040 | ...

Material developments

Approaches to reducing the traditional dependence on primary heavy rare earth materials and associated sintered magnet production include increasing the level of recycled materials, the use of secondary rare earth materials and alternative manufacturing methods such as polymer bonding.

Material Developments
- Windings
- Hard Magnetics
- Soft Magnetics

1

Reducing reliance on vulnerable rare earth materials

Heavy rare earth materials such as dysprosium and terbium are added to improve the temperature resistance of neodymium but are expensive and strongly concentrated in China. There is a desire that the use of heavy rare earth materials should be eliminated to reduce costs and supply risks. In the short term, some OEMs such as Toyota are adding cerium and lanthanum to shield themselves from potential price spikes, even phasing out neodymium.

Using recycled permanent magnets offers an opportunity to diversify the supply chain. In the medium term, only a proportion of recycled rare earth materials will feasibly operate in an electrical machine, with a sizeable quantity of primary rare earth materials needed to maintain performance. The long-term ambition would be to design permanent magnets based on 100% recycled material that maintains high-temperature capability and high flux densities. This would enable a closed-loop supply chain for rare earth materials, improving the cost and environmental performance of permanent magnet machines, making them a long-term LCA-compliant option.

1 Reduced heavy rare earths content → Blends of primary and secondary rare earth magnets → 100% recycled rare earth magnets

2 Alternatives to sintered NdFeB for mass market applications (e.g. iron ferrite, SmCo, bonded NdFeB)

2

Alternatives to sintered magnets

Except for a few outliers, most permanent magnets in EV traction motors are sintered NdFeB magnets. IP for this manufacturing method is highly protected, with a supply chain that is dominated by a select few players in China and Japan. Manufacturing complex magnets like this is extremely labour intensive and wastes some of the alloy material due to various grinding and slicing techniques used.

Alternative magnet manufacturing methods, that diversify away from the sintered route, could prove attractive for automotive traction electric machines. Cost-effective iron ferrite magnets have been trialled on various InnovateUK projects and used for the lower-powered motor in the hybrid Chevy Volt. Given the lower flux density, the magnets are considerably heavier and cannot act as a direct drop-in for NdFeB. Samarium cobalt magnets have also been used for high-temperature 48V-based motors, but they command a price premium and are considered more suitable for aerospace applications.

Polymer-bonded NdFeB magnets can be a further cost-effective alternative. Complex shapes can be manufactured, sometimes directly in the e-machine, without the need for further machining. Its supply chain is less prone to price spikes due to the absence of heavy rare earths like dysprosium, but the motor needs to be designed with these magnets in mind to optimise performance. A challenge with polymer-bonded NdFeB is recycling the magnets so they are LCA compliant.

2020

Material developments

Enhancement of current electrical steels can deliver greater overall machine efficiency. Soft magnetic composites and next-generation electrical steels produced with new advanced manufacturing methods provide the potential for higher performance.

Machine Architectures and Integration

Thermal Management

Material Developments: Windings, Hard Magnetics, Soft Magnetics

Manufacturing Innovations

Life Cycle

1 Innovation trajectories for electrical steels

Advances in the magnetic and chemical properties of electrical steels can reduce eddy and hysteresis losses, improving overall machine efficiency. Short-term challenges include automotive relevant measurement methods and material models/characterisation, improved bonding and coating technologies (e.g. self-bonding coatings), achieving lower-loss thinner grade steels and higher alloy content grades for automotive volume.

Longer-term challenges include utilising more grain-orientated steels, introducing other metals that are cost effective and developing tailored steels with localised optimisation. Amorphous conductive metals that are cooled so quickly they eliminate the grains are also promising for high-performance applications. These can be adapted for alternative manufacturing methods such as ALM or continuous casting processes. The difficulty is scaling them up so they can be cost effectively used in automotive applications.

1 Enhanced e-steels (i.e. higher Si content, thinner laminations) → Cost competitive next gen. e-steels (e.g. CoFe alloys, localised properties)

2 SMCs tailored for high volume automotive (i.e. smaller grain sizes, reduced saturation)

2 Soft magnetic composites suited for automotive propulsion

Soft magnetic composites are less commonly used in automotive applications compared to electrical steels, but they do allow more complex, 3D shapes to be manufactured through net-shape manufacturing. Challenges include improving losses and permeability, reducing grain sizes and achieving significant cost reduction in the manufacturing processes.

2020 | 2025 | 2030 | 2035 | 2040 | ...

Manufacturing innovations

Alternative winding strategies and pre-formed or 3D printed windings could deliver improved performance, while new production methods are needed to deliver higher material yields for stators and rotors.

Machine Architectures and Integration

Thermal Management

Material Developments: Windings, Hard Magnetics, Soft Magnetics

1

Winding techniques to achieve economies of scale

Winding strategies (e.g. distributed, concentrated) are key to maximising performance and reducing machine losses. Key challenges include increasing material fill factor and fully automating the manufacturing process to enable lower-cost machines. To complement the winding processes, better impregnation techniques (e.g. trickle impregnation) that eliminate resin waste, reduce energy consumption and maximise floor space are required.

Both pre-formed casted windings and 3D printed windings offer the potential for a step change in performance, resulting from the optimisation of the material usage and the ability to form complex geometries.

2

Improved material efficiency of stator and rotor production

Existing stator- and rotor-stamping techniques for electrical steels are highly inefficient, with the highest material yields being 70%. Hybrid and EV designs typically have 0.25 mm to 0.30 mm thickness laminations. This is pushing traditional rolling and stamping equipment to the limit; with higher failure rates, reduced throughput and lower yields. Laser cutting could potentially be a solution, but it is expensive and cannot manufacture laminations at rates similar to stamping and is therefore mainly used for niche applications.

A long-term ambition is to have net-shape, zero-waste magnetic materials that integrate both hard and soft magnetic materials into the rotor or stator. This requires advancements in powder metallurgy or using advanced additive-layer manufacturing techniques.

Manufacturing Innovations

- 1 High volume winding techniques with high fill factor (e.g. cont. hairpin) → New winding processes for high performance (e.g. casted windings, ALM)
- 2 Reduced wastage of stator / rotor stacking (e.g. slinky stators) → Net shape, zero waste integrated magnetics
- Enhanced magnet manufacturing processes (e.g. laminations)
- Reduced wet manufacturing processes in machine assembly → Eliminate wet processes

Life Cycle

2020 | 2025 | 2030 | 2035 | 2040 | ...

Manufacturing innovations

New manufacturing processes for permanent magnets are needed. Reducing reliance on wet processes in motor assembly could increase the efficiency of production and make disassembly and recycling easier.

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Electric Machines | Technology Roadmap

Machine Architectures and Integration

Thermal Management

Material Developments: Windings, Hard Magnetics, Soft Magnetics

3

New ways to manufacture permanent magnets

Advances in manufacturing processes for permanent magnets could help to realise lower eddy current loses through lamination and improvements in strength, durability and high-temperature capability. See Alternatives to sintered magnets for other magnetic materials and their manufacturing methods.

For ultra-high-performance applications, the use of superconducting magnets could be used to maximise the energy from a battery pack or fuel cell system.

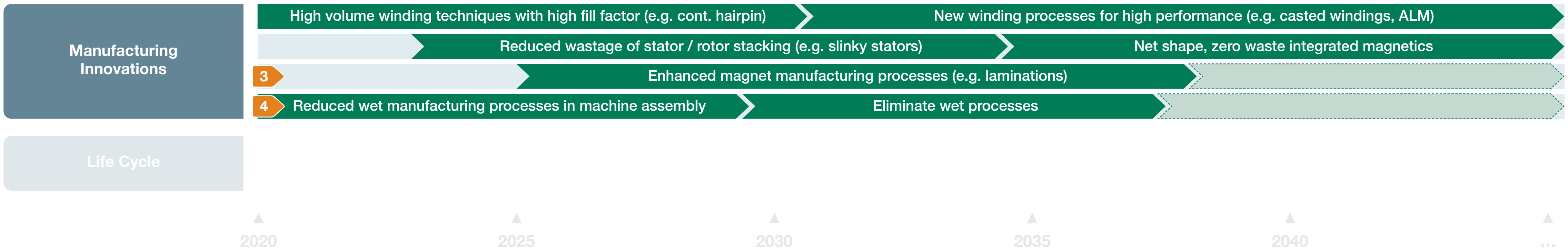
4

Reducing and removing wet processes in motor assembly

Wet processes introduce complexity into high-volume production assembly lines. Removing resins, greases, additives and bonding materials would improve motor production speeds and reduce the costs, as managing curing times and handling these chemicals safely takes time and adds cost.

Eliminating magnet adhesives by using dry retention methods (e.g. mechanical joining techniques) or removing impregnation materials by pre-treating coils with thermal materials are all potential options to remove wet processes during assembly.

Removing these chemicals also makes it easier to disassemble electric machines at the end of life. For example, impregnation materials embed the windings into the stator slots and make it harder to extract the copper.



Life cycle

Recycling electric machines economically with minimal environmental impact is challenging, although several routes are emerging. Design for disassembly and recycling will be important in the short term. Over the long term, life cycle assessment across the entire value chain will be vital.

Roadmap 2020
Electric Machines | Technology Roadmap

Machine Architectures and Integration

Thermal Management

Material Developments: Windings; Hard Magnetics; Soft Magnetics

Manufacturing Innovations

1

High volume recycling methods

As vehicles become increasingly electrified, high-volume solutions for recycling electric machines is needed. The challenge is extracting magnets, copper and electrical steels cost effectively without damaging any of the materials. Therefore, when high-volume recycling processes are scaled up, they need to both minimise environmental impact (using no harmful chemicals or energy-intensive processes) and have high recovery rates of both critical and non-critical materials. The challenge for industry is doing all this while still being economically viable.

Many innovative methods are emerging for rare earth recycling. These range from injecting hydrogen to break magnets down, to using solvent extraction processes. The issue for rare earth materials is ensuring the quality can be maintained – the final goal is a full circular economy without using primary rare earth materials. Copper can be recycled many times without degrading, although the impregnation makes it difficult to extract the material.

A key challenge is ensuring that electrical steels can be adequately disassembled and recycled. Given the layers of insulation between each lamination and the higher silicon content, it cannot be recycled with traditional steel grades. New processes for recycling electrical steels therefore need to be developed.

2

Machines designed for LCA and net-zero CO_2

If machines are designed for disassembly and minimal environmental impact from the beginning, it makes the recycling step much easier. This includes using reversible adhesives and impregnation materials and making the components easier to disassemble.

Current electric machine designs, such as interior permanent magnet machines, are difficult to recycle as the magnets are embedded inside the rotor and glued with strong adhesives. This makes mechanical extraction processes difficult as the magnets are too brittle and can break. While heat treatment processes are available that can make the magnets more amenable to extraction, these processes emit fumes from the heated adhesives which are environmentally unfriendly; moreover, prolonged heat can cause the magnets to uncontrollably fly off the rotor.

Decarbonising the electric machine value chain is also vital. Steel, copper and magnet manufacturing processes are all extremely energy intensive. Either low-carbon energy sources will be needed, or alternative manufacturing processes with low energy footprint.

Life Cycle

1. Pilot recycling plants → Mass market e-machine recycling → Closed loop value chain for e-machines
2. Design for LCA and disassembly → Highly decarbonised manufacturing and recycling → LCA focussed value chains

2020 | 2025 | 2030 | 2035 | 2040 | ...

Glossary

Abbreviation	Explanation
ALM	Originally used for rapid prototyping, additive layer manufacturing creates three dimensional parts by assembling numerous two-dimensional layers. There are numerous forms of additive layer manufacturing that range from 3D printing to electron beam melting.
dV/dt	The rate at which voltage changes over time.
LCA	Life-cycle assessment. Assessing environmental impacts over all stages of the life-cycle of a product (for instance from raw material extraction, through processing, to manufacture, use and ultimately recycling/disposal).
NdFeB magnet	The most widely used permanent magnet made from an alloy of neodymium (rare earth), iron and boron.
SMC	Soft magnetic composites are ferromagnetic powder particles coated with an insulating layer which can be formed into complex shapes.
WLTP	The world harmonised light-duty vehicles test procedure is a global standard for establishing the fuel consumption, pollutant levels and CO_2 emissions of IC and hybrid cars and the range of fully electric vehicles.

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This is an industry consensus roadmap facilitated by the APC

Summary of engagements during the 2020 roadmap refresh

Spread of companies that participated in the refresh

109 industry organisations participated in Workshops and Interviews

38 additional industry organisations participated via the Online Survey

Total engagements 147 Industry Organisations

A global view with international participation

- Austria
- Belgium
- England
- Germany
- Netherlands
- Scotland
- Singapore
- Sweden
- Switzerland
- United States
- Wales
- Japan